CHAPTER VI

SHOCK EFFECTS OF SURFACE AND SUBSURFACE BURSTS

CHARACTERISTICS OF SURFACE AND SHALLOW UNDERGROUND BURSTS

INTRODUCTION

6.01 Surface and shallow underground bursts are defined as those in which either the fireball or the hot, high-pressure gases generated by the explosion intersect or break through the earth's surface. In explosions of this type, part of the energy released is spent in producing a surface crater, whereas much of the remainder appears as air blast and ground shock. The greater the depth of the burst point below the surface, the smaller is the energy expended as air blast. The dimensions of the crater increase at first with increasing depth of burial of the weapon, pass through a maximum, and then decrease virtually to zero at still greater depths.

AIR BLAST

6.02 In a contact surface burst (§ 2.127 footnote) the incident and reflected air blast waves coincide immediately, forming a hemispherical shock front as shown in Fig. 3.34. The characteristics of the blast wave accompanying a reference (1 kiloton) explosion, as functions of the distance from ground (surface) zero (§ 2.34 footnote), can then be obtained from the curves given at the end of Chapter III. The cube root scaling law described there can be used to calculate the blast wave properties from a contact surface burst of any specified energy yield. When the burst occurs below the surface, the air blast arises partly from the ground shock transmitted through the surface into the air and partly from the release of the high-pressure gases produced in the explosion. At shallow burst depths the latter effect predominates but with increasing depth of burial it contributes less and less to the air blast. Furthermore, as the depth of burst is increased, the higher overpressures closer to surface zero fall off more rapidly than do the lower overpressures at greater distances. More information concerning the air blast from shallow underground explosions and the effect of yield and burst depth on the spatial distribution of the overpressure is given in § 6.80 *et seq.*

CRATER FORMATION

6.03 The mechanism of crater formation depends on the height or depth of the burst. For an explosion well above the surface but in which the fireball intersects the ground (§ 6.08), a depression crater is formed as a result of the vaporization of considerable quantities of earth material. This material is sucked upward by ascending air currents resulting from the rising fireball and it eventually appears as fallout (Chapter IX). For bursts at or near (above or below) the surface, air blast plays a part in crater formation, in addition to vaporization. Surface material is then removed by being pushed, thrown, and scoured out. Some of this material falls back into the crater and most of the remainder is deposited around the edges to form the lip of the crater or is scattered as loose ejecta beyond the crater.

6.04 When the burst is at such a depth that surface vaporization and scouring by air blast are not significant, several other processes may contribute to the formation of a "throwout" crater. One is the crushing and fracture of the ground material by the expanding compressional (shock) wave. Another important mechanism is spalling, i.e., the separation of earth layers at the surface (§ 2.91). The spalled layers will fly upward and be deposited as ejecta beyond the crater or on the lip, or, for moderately deep burials, they will fall back into the crater itself. If the hot, high-pressure gases formed by the explosion are not vented during the crushing and spalling phases, the expanding gases may force the confining earth upward; thus gas acceleration can contribute to crater formation, as described in § 2.92.

6.05 Finally, deeply buried explosions may lead to a subsidence crater, to a raised mound above the detonation point, or to no permanent displacement of the surface at all. If the collapse of the chimney containing broken and crushed material should reach the surface, a subsidence crater may be formed (§ 2.103). In strong earth material, such as hard rock, the chimney top may not reach the surface; surface displacement may then be only temporary. If bulking of the broken rock occurs, a surface mound may be formed above the chimney (Fig. 6.05).

6.06 The variations in the character of the crater as a result of the changes in the predominant mechanism of crater formation as the depth of burst (DOB) increases are illustrated in Figs. 6.06a through f. The depression crater in Fig. 6.06a is formed mainly by vaporization, with most of the removed material being carried away. In a contact (or near surface) burst, represented in Fig. 6.06b, scouring, etc., by an air blast also contributes to crater formation and some of the material removed falls back into and around the crater. At greater depths (Fig. 6.06c), spallation and gas acceleration become increasingly important and the dimensions of the crater increase. The crater reaches its largest size when gas acceleration is the predominant mechanism of formation, but even then a large quantity of material falls back (Fig. 6.06d). Finally, Figs. 6.06e and f show examples of bulking and subsidence, respectively, for deeper underground explosions.

6.07 Two more-or-less distinct zones in the earth surrounding the crater may be distinguished (see Fig. 6.70). First is the "rupture zone" in which stresses develop innumerable radial

Figure 6.05. SULKY event; mound created by the bulking of rock material in a 0.087-kiloton nuclear detonation at a depth of 90 feet.

cracks of various sizes. Beyond the rupture zone is the "plastic zone" in which the stress level has declined to such an extent that there is no visible rupture, although the soil is permanently deformed and compressed to a higher density. Plastic deformation and distortion of soil around the edges of the crater contribute to the production of the crater lip. The thicknesses of the rupture and plastic zones depend on the nature of the soil, as well as upon the energy yield of the explosion and location of the burst point. If the earth below the burst consists of rock, then there will be a rupture zone but little or no plastic zone.

CRATER DIMENSIONS

6.08 For an explosion above the earth's surface, appreciable formation of a vaporization (depression) crater will commence when the height of burst is less than about a tenth of the maximum fireball radius (§ 2.127). With decreasing distance from the surface, the dimensions of the crater vary in a complex manner, especially as the ground is approached, because of the change in the mechanism of crater formation. In general, however, the depth of the depression increases rapidly with decreasing burst height and the ratio of the depth to radius also increases. The dimensions of the crater increase with the explosion

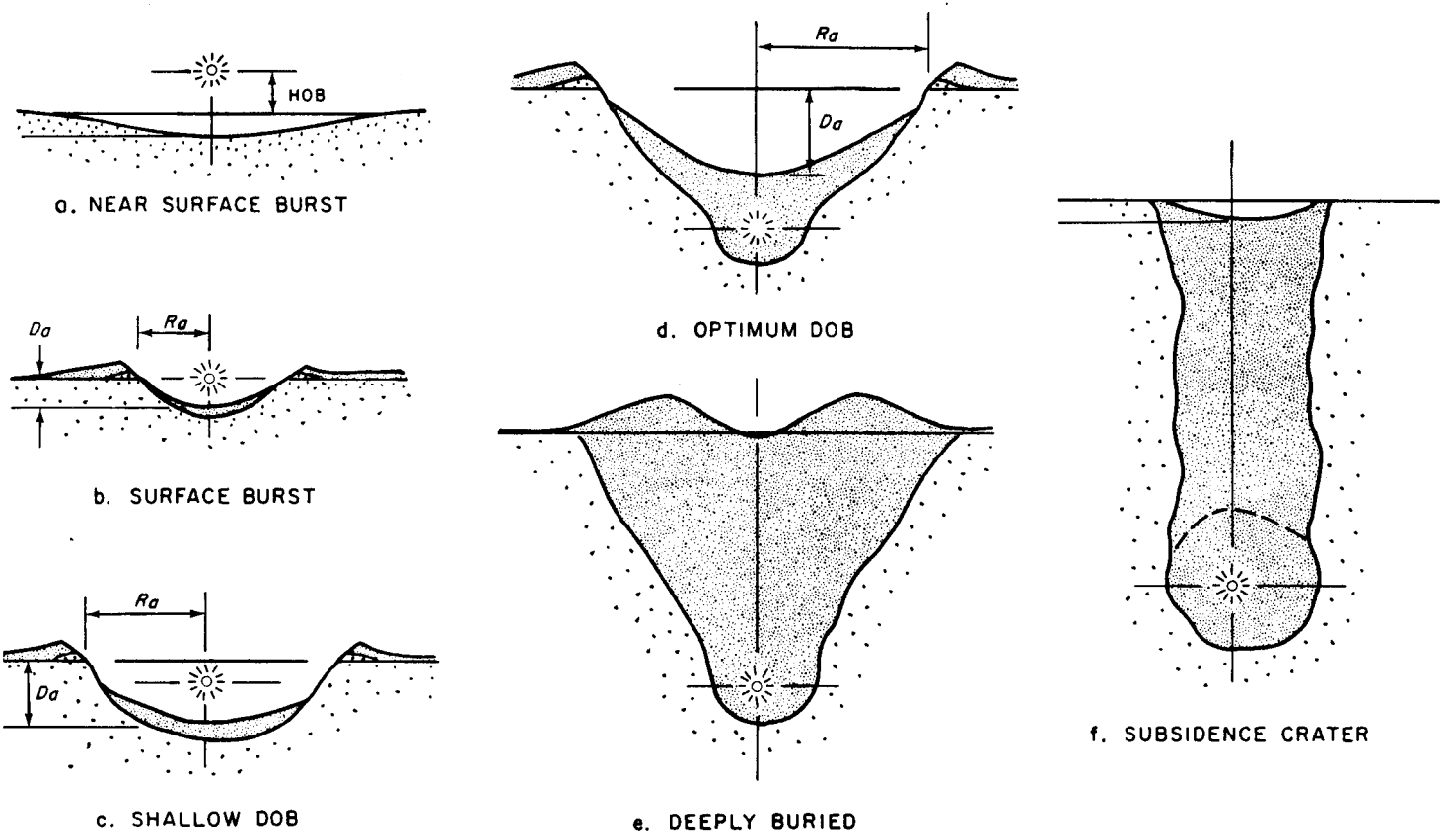

Figure 6.06. Relative crater sizes and shapes resulting from various burst depths; R_a and D_a are the apparent radius and depth, respectively, of the crater (see Figure 6.70).

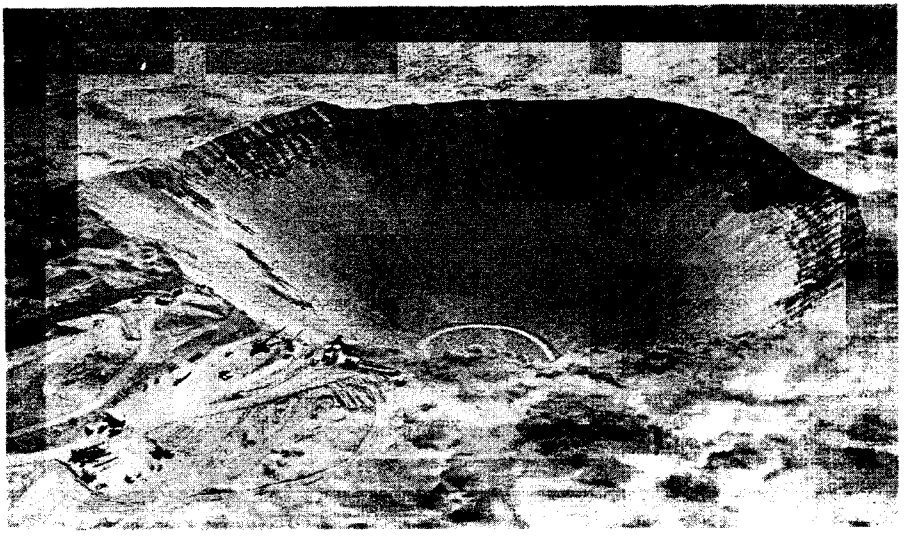

Figure 6.10. SEDAN event; crater formed by a 100-kiloton explosion in alluvial soil at the optimum depth of burst (635 feet) for cratering. The crater radius is 611 feet, the depth 323 feet, and the volume 179 million cubic feet.

yield but the actual values depend on the soil characteristics.

6.09 For contact surface bursts, approximate values of the crater dimensions can be given. For a 1-kiloton nuclear explosion at the surface, the apparent radius of the crater in dry soil or dry soft rock is estimated to be about 60 feet. The radius at the crest of the lip will be 15 feet or so greater. The apparent depth of the crater is expected to be about 30 feet. In hard rock, consisting of granite or sandstone, the dimensions will be somewhat less. The radius will be appreciably greater in soil saturated with water, and so also will be the initial depth, to which structural damage is related. The final depth, however, will be shallower because of "hydraulic fill," i.e., slumping back of wet material and the seepage of water carrying loose soil. All crater dimensions resulting from a surface burst of yield W kilotons are related approximately to those given above for a yield of 1-kiloton by the factor $W^{0.3}$. For example, for a 100-kiloton explosion on the surface of dry soil, the radius of the crater may be expected to be roughly $60 \times (100)^{0.3} = 240$ feet, and the depth about $30 \times (100)^{0.3} = 120$ feet. Further information on crater dimensions will be found in § 6.72 *et seq.*

6.10 As the depth of burial is increased, the radius and depth of the crater also increase until maxima are reached; deeper burial then results in progressively smaller craters. These maximum values of radius and depth for a given yield are termed "optimum" (Fig. 6.06d) and depths of burial for optimum crater radius and for optimum crater depth are roughly equal. A photograph of a crater formed at the optimum burst depth is shown in Fig. 6.10. For a 1-kiloton weapon, the

deepest crater possible, namely, 100 feet, is produced when the burst point is 120 feet below the surface; the radius of the crater at that depth will also be near its optimum, namely about 160 feet. Optimum values, like all crater dimensions, are approximately proportional to $W^{0.3}$. Curves showing the variations of crater radius and depth with depth of burial in various media appear later in this chapter (§ 6.70 *et seq.*).

6.11 If the soil is saturated and the high water table is maintained after the detonation, the crater dimensions will change with time. Slumping of the crater sides will continue until a stable condition exists for the material. It can be expected that the sides of very large craters will ultimately slump until their slopes decrease to 10 to 15 degrees. As a result, the craters will become shallower and broader. In weak saturated soil with a very high water table, slumping occurs immediately. If the soil is stronger and the water table not too high, there is a time lag in the slumping which may be a matter of hours in sands and months in clay soils. Examination of craters in coral from high-yield bursts at the Eniwetok Proving Grounds has shown that the inward rush of water carries material which would normally constitute the crater lip into the bottom of the crater.

GROUND SHOCK

6.12 A nuclear explosion on or near the surface produces a ground shock in two primary ways, each of which sets the earth in motion; they are (1) by direct coupling of explosive energy to the ground in the neighborhood of the crater, and (2) by pressure of the air blast wave as it runs over the earth's surface. A random type disturbance is often superimposed on the ground motion resulting from these shocks (§ 6.82) but only the latter will be considered here. Each kind of ground shock (or pressure) is transmitted through the earth downward and outward. The direct ground shock contributes to the formation of the crater and the fracture and plastic zones immediately around it. The air blast pressure, called "airslap," is the source of most of the stress on underground structures beyond the crater area when the burst point is not too deep.

6.13 Although shock waves transmitted through the earth may be greatly complicated and distorted by the presence of geological inhomogeneities, certain regularities tend to be found. Airslap, for example, almost always results in a single movement downward followed by a slower, partial relaxation upward; in some soils residual permanent compression after airslap is measurable and significant. The amount of earth motion depends on the air blast overpressure, the positive phase duration, and the character of the soil. Close to the surface, airslap motion is initially abrupt, similar to the rise of pressure in the air shock, but it becomes more gradual with increasing depth.

6.14 In those regions where the air blast wave front is ahead of the direct ground shock front at the surface, the situation is described as being "superseismic;" that is to say, the air blast wave is traveling at a speed greater than the speed of sound (or seismic velocity) in the earth. The ground motion near the surface is vertically downward, but it becomes increasingly outward, i.e., ra-

dial, from the burst point at greater depths below the surface.

6.15 On the other hand, when the air blast front lags behind the shock front transmitted directly through the ground, the ground wave is said to "outrun" the air blast. The airslap then causes the ground surface at locations ahead of it to undergo a characteristic outrunning motion, generally consisting of two or three cycles of a damped, i.e., decreasing, undulation with the first motion usually upward. Since the air blast overpressure decreases with increasing distance from surface zero, so also does the outrunning motion. If the air blast wave reaches the observation point while the outrunning surface motion is still underway, the airslap motion will be superimposed on the undulations.

6.16 At locations close to the burst, the air blast usually travels faster than the direct ground shock. The superseismic condition then prevails and the first ground motion is determined essentially by the airslap. At greater distances, the air blast weakens and its velocity decreases significantly, but the ground shock velocity, which is approximately the same as the sesimic velocity, does not decrease very much. Hence, the ground shock front moves ahead and outrunning becomes the dominant factor in ground motion. At still greater distances from surface zero, the effect of airslap disappears or it is so weak that it merges with the direct ground shock without causing any outrunning motion. The phenomena described above are strongly influenced by the seismic velocities in the ground down to considerable depths.

6.17 The strength of the shock wave in the ground decreases with increasing distance from the explosion, and at large distances it becomes similar to an acoustic (or seismic) wave. In this region the effects of underground shock produced by a nuclear explosion are somewhat similar to those of an earthquake of low intensity. However, the evidence to date indicates that underground explosions do not cause earthquakes, except for minor aftershocks within a few miles of the burst point (§ 6.20 *et seq.*).

6.18 The effect of ground shock pressure on an underground structure is somewhat different in character from that of air blast on a structure above the ground. In the latter case, as explained in Chapter IV, the structure experiences something like a sudden blow, followed by drag due to the blast wind. This type of behavior is not associated with underground shock. Because of the similarity in density of the medium through which a ground shock wave travels and that of the underground structure, the response of the ground and the structure are closely related. In other words, the movement (acceleration, velocity, and displacement) of the underground structure by the shock wave is largely determined by the motion and containing action of the ground itself. This fact has an important influence on the structural damage associated with both surface and underground explosions. Damage criteria are outlined in § 6.28 *et seq.* and are discussed more fully in § 6.90 *et seq.*

DEEP UNDERGROUND BURSTS[1]

GROUND SHOCK

6.19 In a fully-contained deep underground explosion there would be little or no air blast. Much of the energy is expended in forming the cavity around the burst point and in melting the rock (§ 2.102), and the remainder appears in the form of a ground shock wave. As this shock wave moves outward it first produces a zone of crushed and compressed rock, somewhat similar to the rupture zone associated with crater formation (Fig. 6.70). Farther out, where the shock wave is weaker, the ground may become permanently distorted in the plastic (deformation) zone. Finally, at considerable distances from the burst point, the weak shock wave (carrying less than 5 percent of the explosion energy) becomes the leading wave of a series of seismic waves. A seismic wave produces a temporary (elastic) displacement or disturbance of the ground; recovery of the original position, following the displacement, is generally achieved after a series of vibrations and undulations, up and down, to and fro, and side to side, such as are typical of earthquake motion.

AFTERSHOCKS AND FAULT DISPLACEMENTS

6.20 Many of the aftershocks associated with a deep underground explosion appear to be directly related to the postdetonation phenomena of cavity collapse and chimney growth (§ 2.103). Some aftershocks, however, originate a few miles beyond the region involved in the development of the chimney. These aftershocks are generally considered to result from small movements along preexisting fault planes[2] and to represent the release of natural strain (deformation) energy. For explosions of high energy yields aftershocks may continue, although at a reduced rate, for many days after the chimney has formed.

6.21 The 1.1-megaton BENHAM test was conducted at a depth of 4,600 feet in tuff (§ 2.104) at the Nevada Test Site on December 19, 1968. During the period of six weeks following the detonation, some 10,000 weak aftershocks were detected, nearly all within 8 miles of the explosion point. Of these, 640 aftershocks were chosen for detailed study and their locations are shown by the small crosses in Fig. 6.21. The thin lines indicate positions of known faults and the thick lines show approximately where fault displacements were observed at the surface. It is apparent that a large number of the aftershocks occurred along a north-south line, which is the general direction of the known faults. Many of these aftershocks presumably occurred along hidden faults or other geological discontinuities parallel to the faults.

[1] The phenomena and effects of deep (fully contained) underground explosions are of primary interest for nuclear weapons tests. For a more detailed nontechnical discussion see "Public Safety and Underground Nuclear Detonations," U.S. Atomic Energy Commission, June 1971, TID–25708.

[2] A geological "fault" is a fracture in the ground at which adjacent rock surfaces are displaced with respect to each other. The presence of a fault can sometimes be detected by a fault line on the surface, but hidden faults cannot be observed in this way.